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Coding and Synchronization Analysis of the NILE UHF Fixed-Frequency Waveform

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13. ABSTRACT (Maximum 200 words)

The NILE UHF fixed-frequency waveform employs an RS (48,30) error control code with 8-bit characters. The code is used both to correct errors and to identify when the decoder has failed to produce a correct codeword. When this code is used on a memoryless binary symmetric channel, the probability of codeword error is 10^{-5} when the channel bit error probability is 0.5%, and the probability of undetected decoder error is upper bounded by 2.8 (10^{-6}) for all channel bit error probabilities. Synchronization acquisition, employing a 255-bit reference sequence, is far more tolerant to bit errors than the waveform itself. The probability of false synchronization in a random noise environment is less than 10^{-6} when the correlator threshold is set at 90. With this threshold the probability of missed synchronization is less than 10^{-6} for a 20% channel bit error probability. Synchronization performance is acceptable for truncated received sequences up to truncation levels of 50%.

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Coding and Synchronization Analysis of the NILE UHF Fixed-Frequency Waveform

1. Coding Analysis

1.1 Probability of Codeword Error

The NILE UHF Fixed-Frequency 16kbps waveform employs an RS(48,30) error control code. In this code, thirty 8-bit information bytes are encoded by appending eighteen 8-bit parity check bytes to form a codeword of length forty-eight 8-bit bytes. (This is a shortened version of an RS (255,237) code with 207 all-zero information bytes that are not transmitted.) The code has a minimum distance equal to nineteen bytes so that it can correct as many as nine byte errors.

We assume that the coding channel is a memoryless binary symmetric channel (BSC) with (channel) bit error probability p. A byte error will occur if there are one or more bit errors within the byte. That is, a byte will be received correctly only if all eight bits are correct. The probability of byte error is given by

$$P_B = 1 - (1-p)^8. \tag{1}$$

Since the code can correct up to nine byte errors, the probability of codeword error is given by

$$P_{cw} = \sum C_{48,i} \, P_B^i \, (1-P_B)^{48-i} \quad , \tag{2}$$

where $C_{48,i}$ is the binomial coefficient 48!/i!(48-i)!, and the summation is taken from $i = 10$ to $i = 48$.

The graphical result of combining (1) and (2) to give the probability of codeword error as a function of channel bit error probability is shown in Figure 1. We see that the codeword error probability performance is acceptable for $p = 0.001$ but degrades rapidly as p increases to 0.01.

In Figures 2 and 3 we see the probability of codeword error plotted against E_c/N_o and E_b/N_o, respectively, when NCBFSK modulation is used on an AWGN channel. Although discriminator detection is used in the system implementation, we present the optimum noncoherent receiver result because the analytical result for the discriminator detector is not known. For the optimum receiver the probability of channel bit error is given by
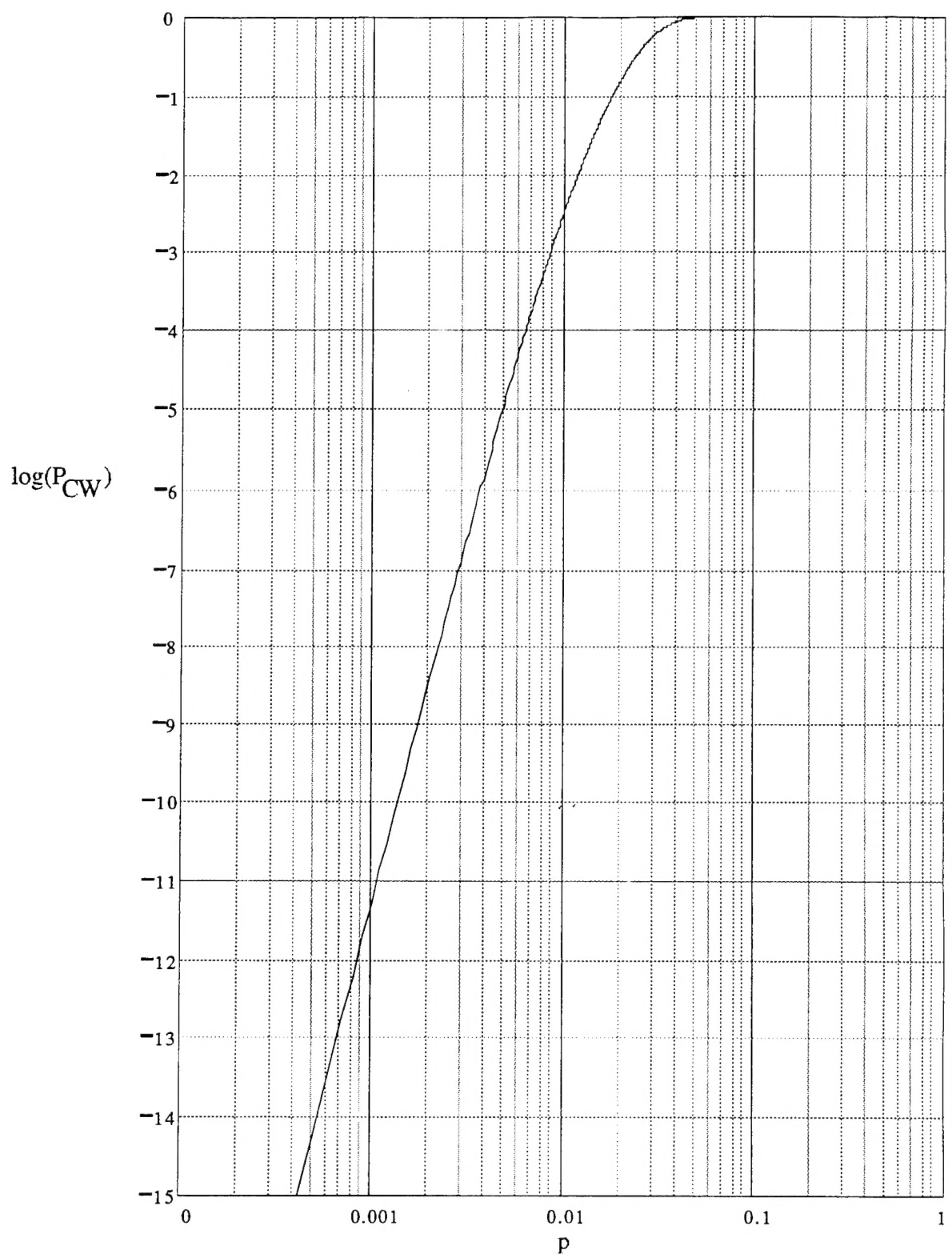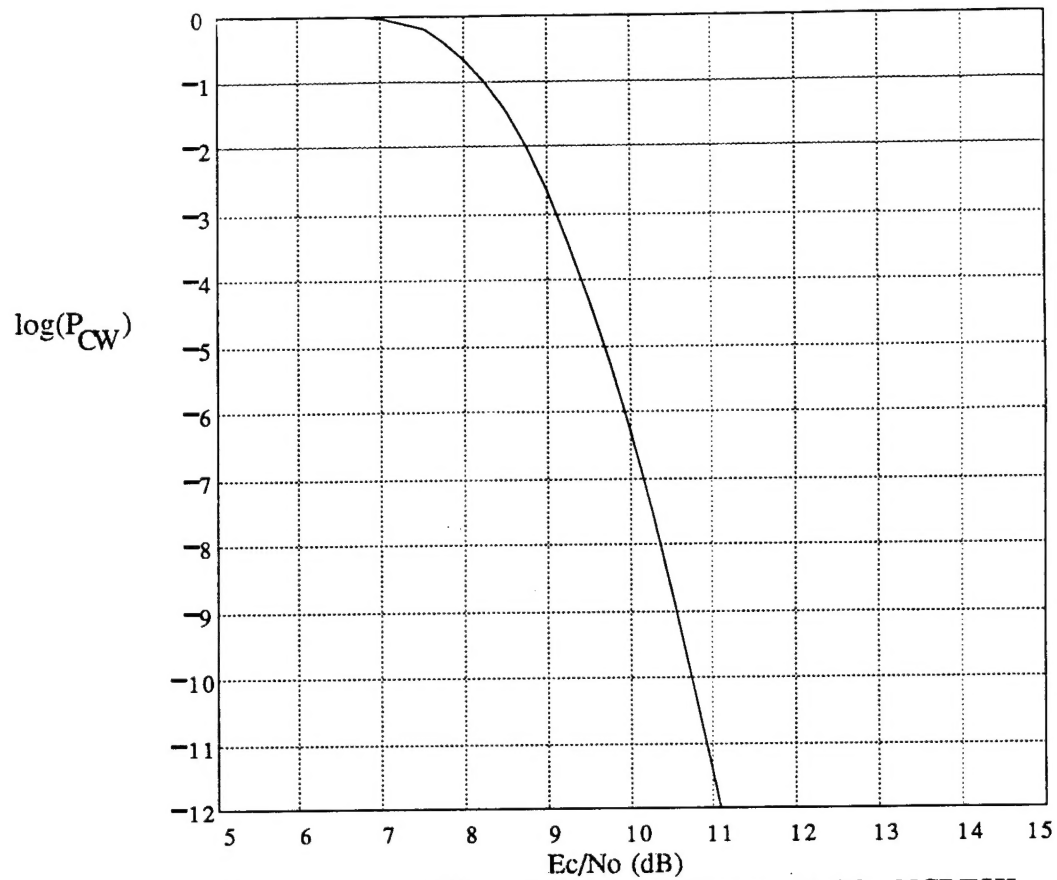
Figure 1.   Probability of Codeword Error versus p.

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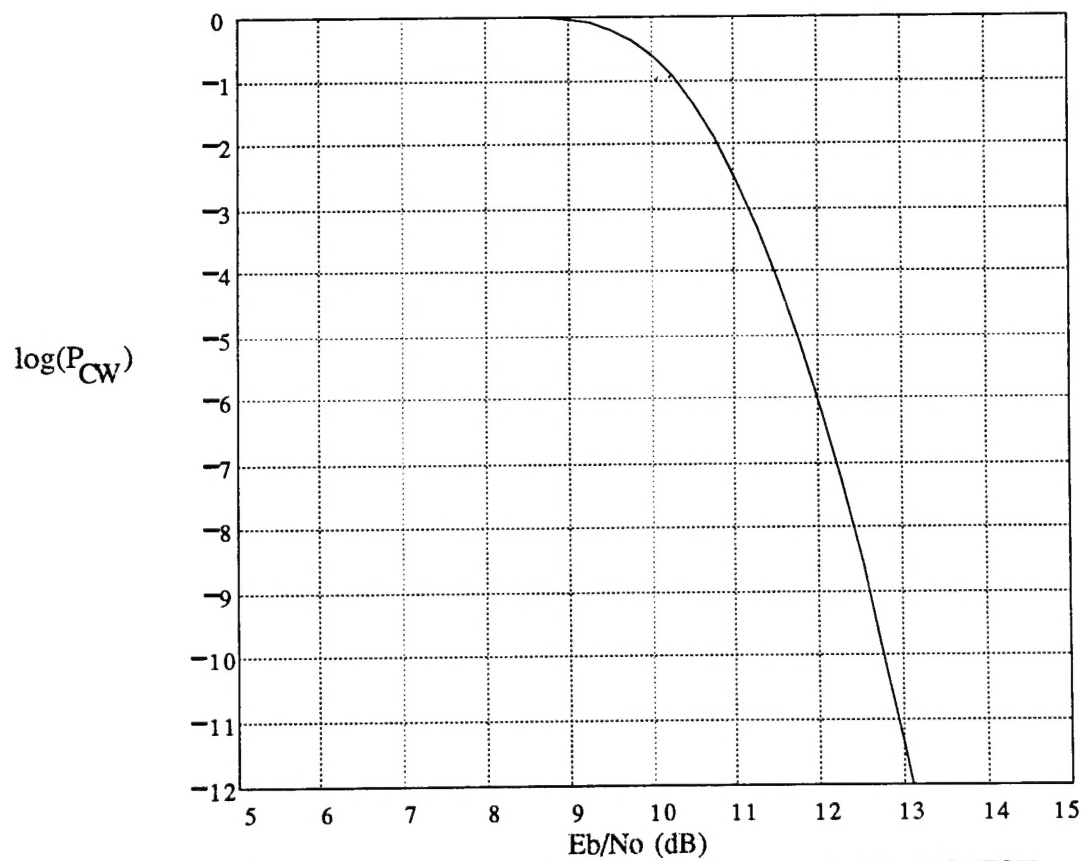Figure 2. Probability of Codeword Error vs. Ec/No, NCBFSK.

Figure 3. Probability of Codeword Error vs. Eb/No, NCBFSK.

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$$p = 1/2 \exp[-1/2\ E_c/N_o], \tag{3}$$

where E_c is the energy per channel bit and N_o is the noise power spectral density. If E_b is the energy per information bit, we can convert the independent variable to E_b/N_o by using $E_b/N_o = 48/30\ E_c/N_o$. We see in Figure 3 that it requires E_b/N_o to be nearly 12 dB for a codeword error probability equal to 10^{-5}.

1.2 Probability of Undetected Codeword Error

When a codeword is not received correctly, one of two events will occur. If the received word falls within an incorrect decoding sphere there will be an undetected decoding error. On the other hand, if the received word falls between decoding spheres, a decoding failure will occur, and this failure will be known to the receiver. The undetected decoding error is the more serious of these two events because the receiver will have misinformation rather than missing information. In general, it is difficult to calculate the probability of undetected decoding error, but there is a simple upper bound [1] for the case of Reed-Solomon codes. This is given by

$$P_{ud} < 1/t! \tag{4}$$

where t is the error correction capability of the code. In the case where $t = 9$, P_{ud} is less than 2.8 (10^{-6}).

1.3 Comments

In the NATO UHF Fixed Frequency application, the Reed-Solomon code is used suboptimally in two ways. First, it is used on a memoryless binary symmetric channel although RS codes are better suited for channels with memory (burst error channels). Second, the decoder is used for pure error correction with no erasure filling, even though the decoder performs better with combined errors and erasures decoding [2]. These two suboptimalities are compensated by the fact that the decoder can be used for detection of decoding failures. This eliminates the need to use a second code (a CRC code) to perform the function of error detection, thereby reducing overhead and complexity.

2. Synchronization Analysis

2.1 Probability of False Synchronization

The acquisition of synchronization is accomplished by correlating the received sequence of bits (with a hypothesized starting point) with a maximal-length reference sequence of length M=255. Synchronization is declared if the number of agreements minus the number of disagreements exceeds a fixed threshold T. If the correlation fails to exceed T, then correlation is repeated on the received sequence with the starting point advanced by one bit. The process continues until the threshold is exceeded (hopefully when correlation is performed with a noisy replica of the received 255-bit maximal-length sequence).

Prior to the arrival of the true sequence, the reference sequence may be correlated with hundreds of hypothesized false sequence starting points. To simplify the analysis, we assume that these false sequences appear as sequences of purely randon coin flips (sequences of equally likely plus and minus ones). When a random sequence is correlated with the reference sequence, the resulting process is a one-dimensional random walk [3], and the correlator test statistic (using the central limit theorem) is a Gaussian random variable with mean = 0 and variance = M. The probability P_1 that this statistic exceeds the threshold T is given by

$$P_1 = Q(T/ M^{1/2}), \tag{5}$$

where $Q(\cdot)$ is the complementary error function [4].

If there are N hypothesized incorrect sequence starting points prior to the correct sequence, each will have a probability P_1 of producing a false synchronization. For N trials, we may closely approximate the total false synchronization probability P_{FS} as

$$P_{FS} = NP_1 = NQ(T/M^{1/2}). \tag{6}$$

The probability of false synchronization, P_{FS}, is plotted against the threshold T in Figure 4. Three values of N (N = 100, 300 and 1000) are shown. It is seen in Figure 4 that for N in the range of 100 to 300 a threshold of T = 90 should be used in order to achieve $P_{FS} = 10^{-6}$.

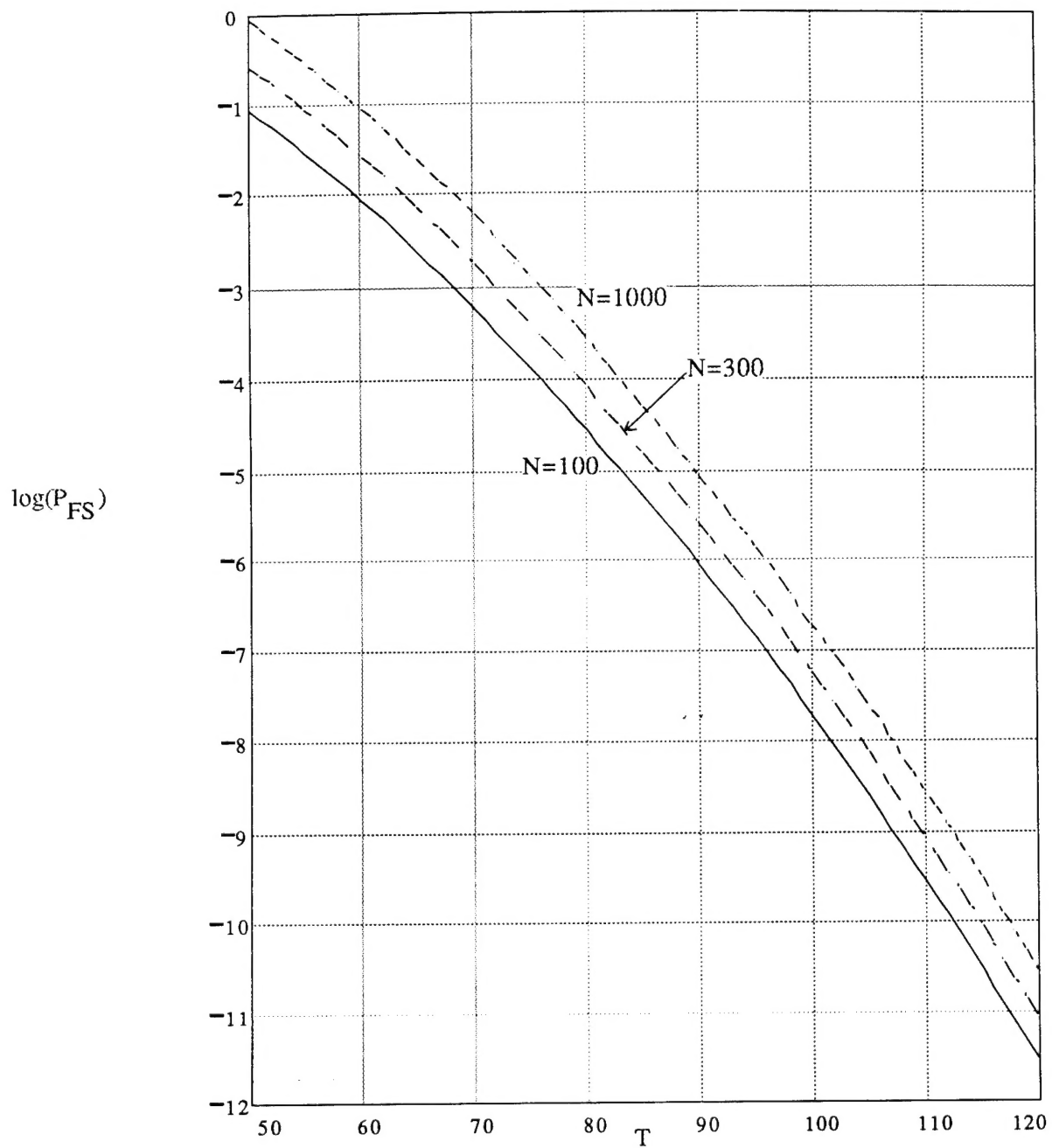Figure 4. Probability of False Synchronization vs. Threshold T; N=100, 300, 1000 trials.

2.2 Probability of Missed Synchronization

We assume that the 255-bit reference sequence is received with bit error probability p. When this noisy replica is correlated with the perfect reference sequence, the probability of agreement is q=1-p, and the probability of disagreement is p. The resulting process is a one dimensional random walk with drift [3], and the correlation random variable is a Gaussian random variable with mean = (2q-1)M and variance = 4pqM. Synchronization will be declared if this random variable exceeds the threshold T established in the previous section. If the correlation statistic falls below T, then there will be a missed synchronization. The probability of missed synchronization is given by

$$P_{MS} = Q\{[(2q-1)M - T]/(4pqM)^{1/2}\}. \qquad (7)$$

Equation (7) is plotted against p in Figure 5 for three values of threshold parameter T. We see that for T=90, P_{MS} is less than 10^{-6} for p=0.2.

2.3 Effect of a Truncated Received Synchronization Sequence

There will be a degradation of synchronization performance if part of the transmitted synchronization sequence of M=255 bits is not received. This could happen, for instance, if the receiver's radio has a slow rise time and it fails to receive the first part of the sequence.

We assume, for simplicity, that only W of the M bits of the noisy replica are received and that M-W are replaced by random bits. In our model, this will not affect the probability of false synchronization or the threshold setting, but the probability of missed synchronization will be increased.

The decision statistic is found by correlating the reference sequence with a noisy replica for a length of W bits and with a random bit sequence for the remaining M-W bits. This produces a Gaussian random variable with mean = (2q-1)W and variance = [4pqW+(M-W)]. We see that the mean is decreased and the variance is increased when we compare to the untruncated case in (7). The probability of missed synchronization for the truncated case is given by

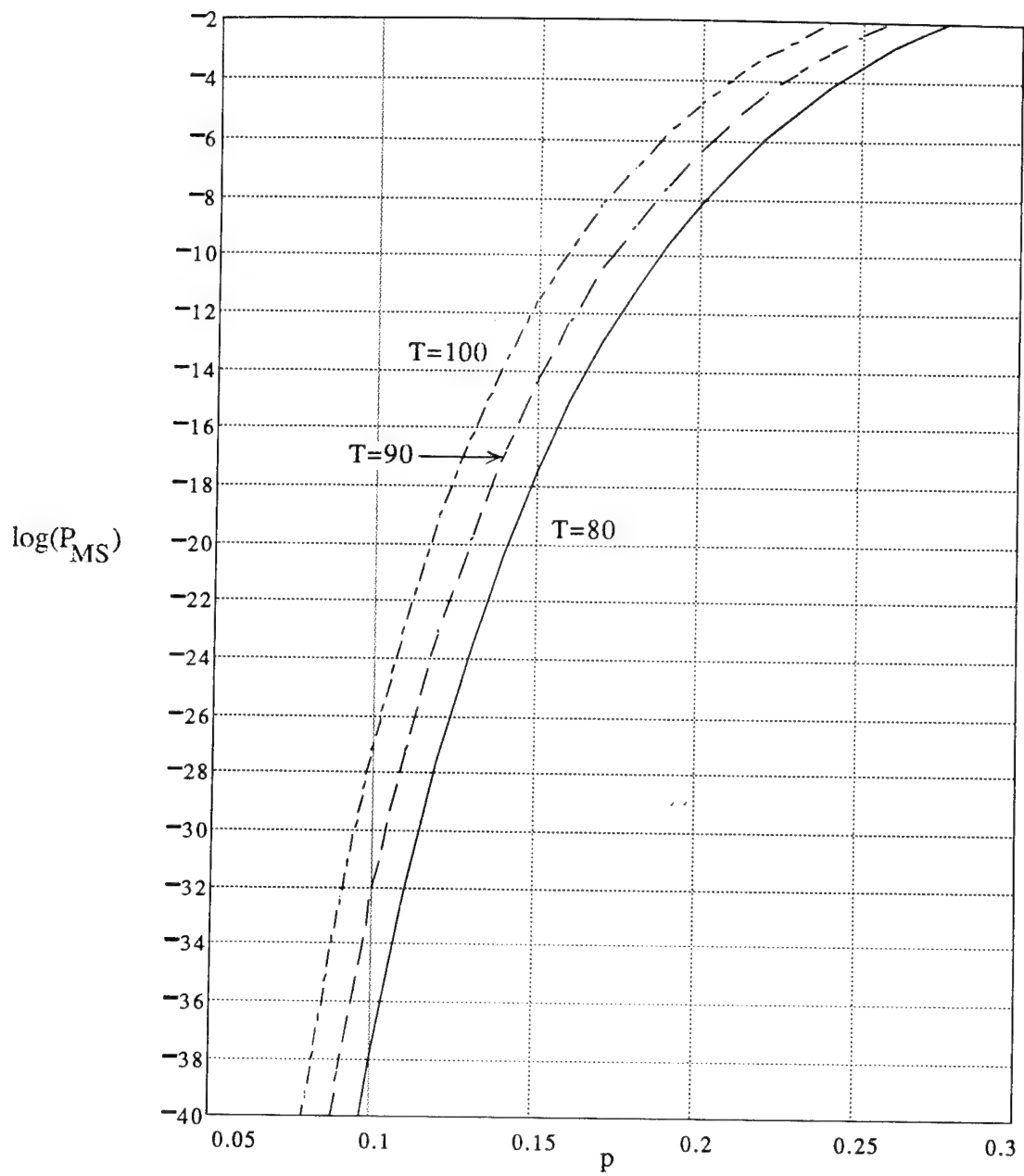$$P_{MS} = Q\{[(2q-1)W-T]/[4pqW+(M-W)]^{1/2}\}. \qquad (8)$$

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Figure 5. Probability of Missed Synchronization with Correct Sequence, versus p, at Thresholds T = 80, 90, 100.

Figures 6-10 show P_{MS} plotted against p for five values of W (W = bM; b=0.9, 0.8, 0.7, 0.6 and 0.5). Each figure has three curves, corresponding to T = 80, 90 and 100. We see in Figure 9 that the performance is acceptable for a 40% sequence loss for a bit error probability p=0.01. Only at a 50% sequence loss will the performance become unacceptable for p=0.01. Figures 11, 12 and 13 show plots of the same data, but with T held constant in each figure. Each figure has five curves corresponding to different values of the parameter W. It can be seen again that the serious degradation occurs only when the truncation is 50% of the received sequence.

3. Final Comments

In comparing the results of Sections 1 and 2, we find that the synchronization design is far more tolerant to bit errors than the coding design. This is true because the RS code is used suboptimally in order that error detection can be performed without using a CRC code. For a bit error probability p=0.01 we can expect that the synchronization will hold up well, even with moderate truncation of the received sequence. The decoder, on the other hand, will make numerous errors, but nearly all of these will be detected and the data will be discarded.

References

[1] R. J. McEliece and L. Swanson, "On the Decoder Error Probability for Reed-Solomon Codes," IEEE Trans. IT, vol. IT-32, no. 5, September 1986.

[2] P. J. Crepeau and K. W. Halford, "Reed-Solomon Coding Preformance with Errors and Erasures Decoding on a Rayleigh Fading Channel," Proc. MILCOM 94, October 1994.

[3] A. Papoulis, *Probability , Random Variables, and Stochastic Processes, 3rd edition*, McGraw-Hill, Inc., 1991.

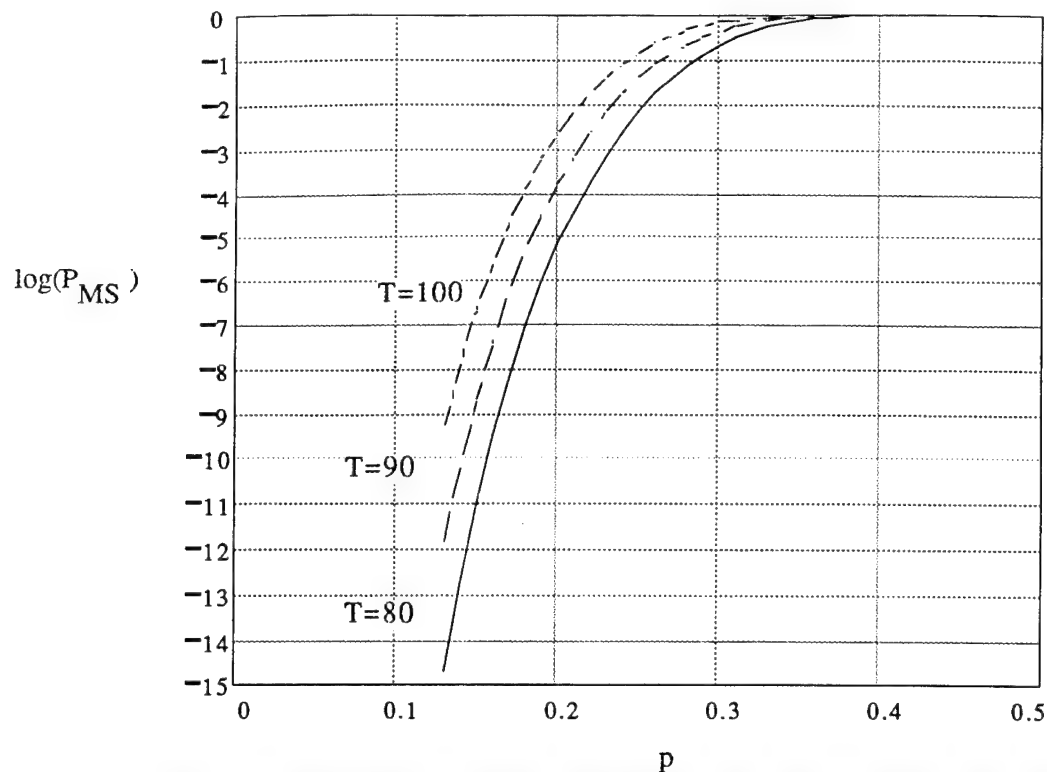[4] J. M. Wozencraft and I. M. Jacobs, *Principles of Communication Engineering*, John Wiley and Sons, Inc., 1965.

Figure 6. Probability of Missed Synchronization with Truncated Sequence, versus p, at Thresholds T = 80, 90, 100. Correlation Length = 90%.
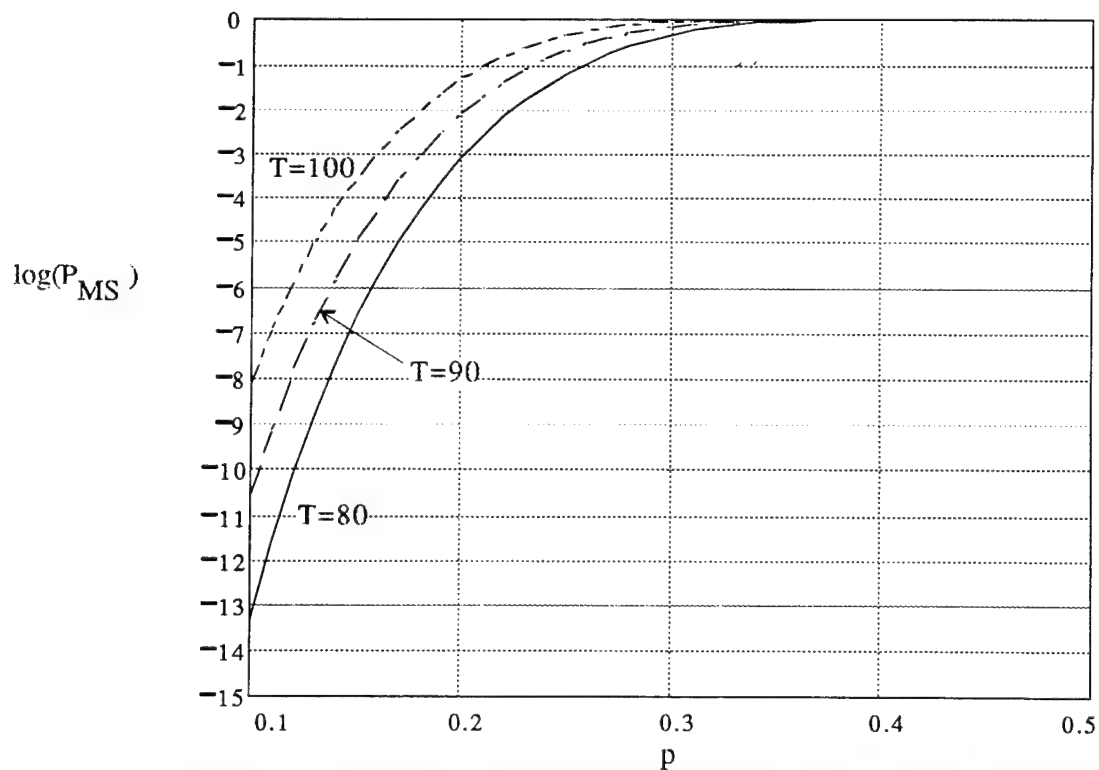

Figure 7. Probability of Missed Synchronization with Truncated Sequence, versus p, at Thresholds T = 80, 90, 100. Correlation Length = 80%.
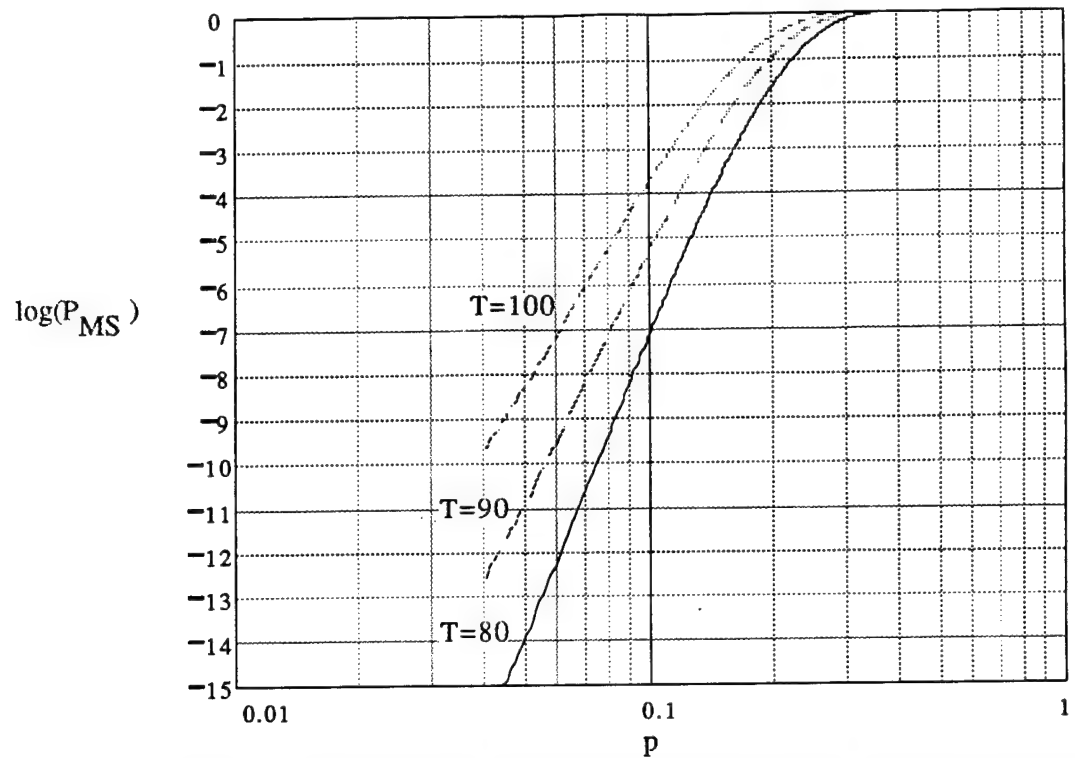
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Figure 8. Probability of Missed Synchronization with Truncated Sequence, versus p, at Thresholds T = 80, 90, 100. Correlation Length = 70%.
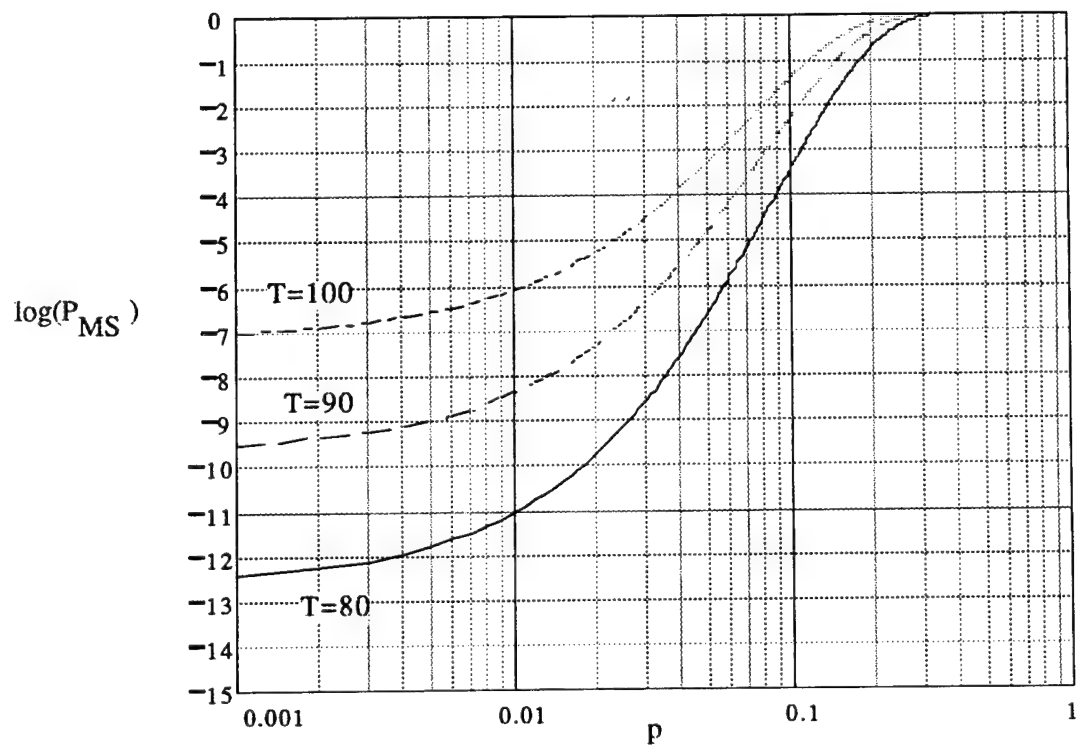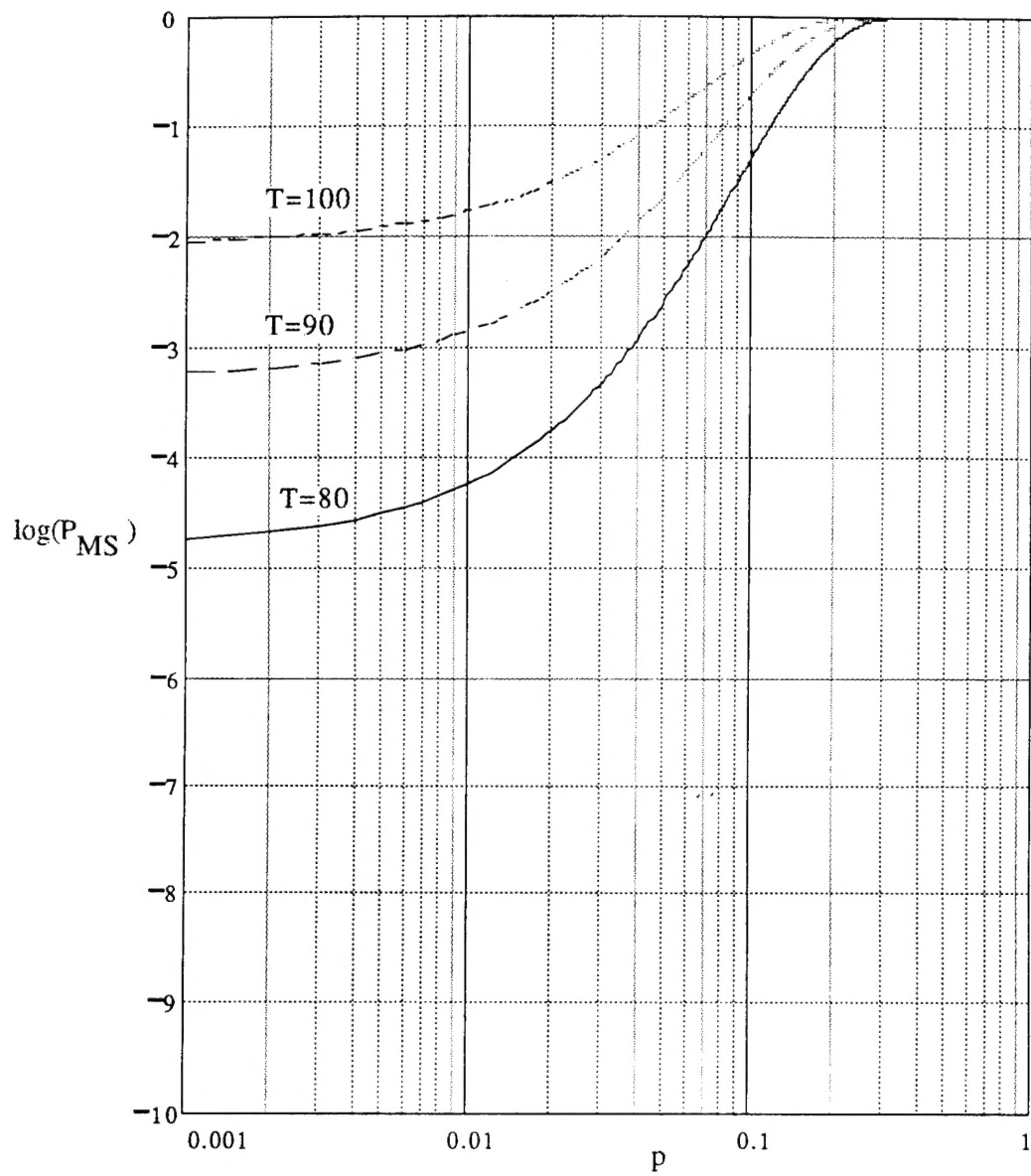

Figure 9. Probability of Missed Synchronization with Truncated Sequence, versus p, at Thresholds T = 80, 90, 100. Correlation Length = 60%.

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Figure 10. Probability of Missed Synchronization with Truncated Sequence, versus p, at thresholds T = 80, 90, 100. Correlation Length = 50%.
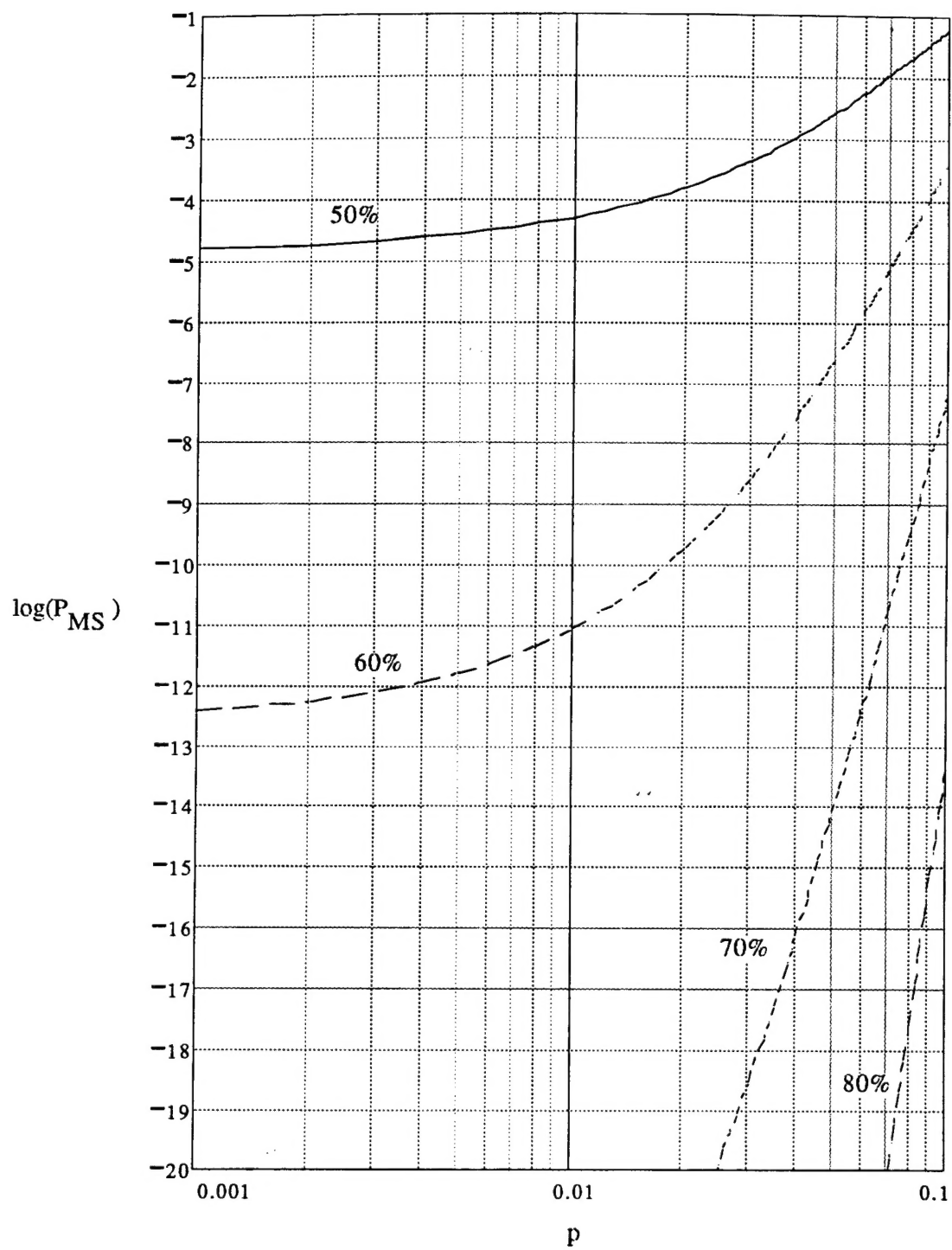
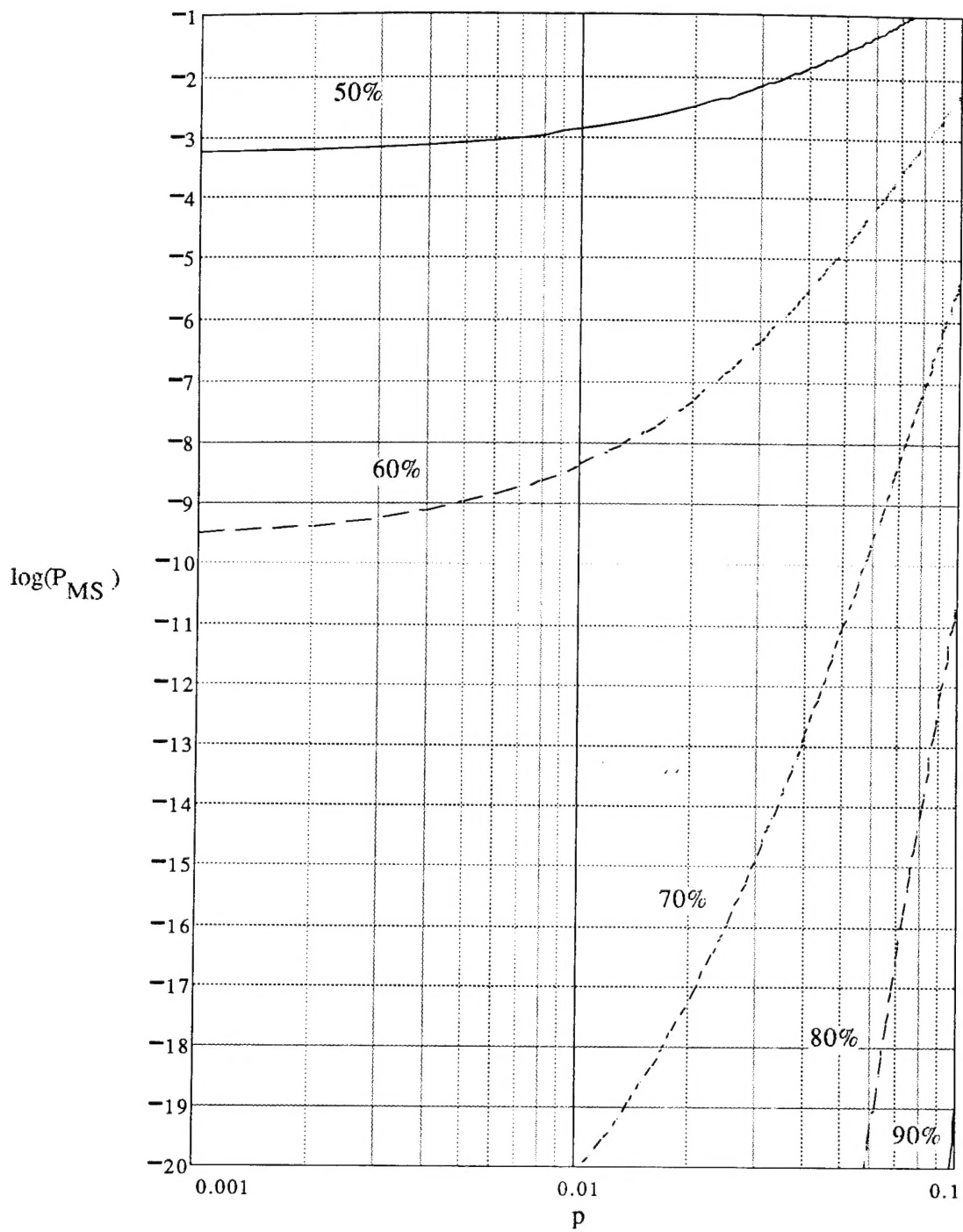Figure 11. Probability of Missed Synchronization with Truncated Sequence, versus p, at Threshold T = 80.

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Figure 12. Probability of Missed Synchronization with Truncated Sequence, versus p, at Threshold T = 90.
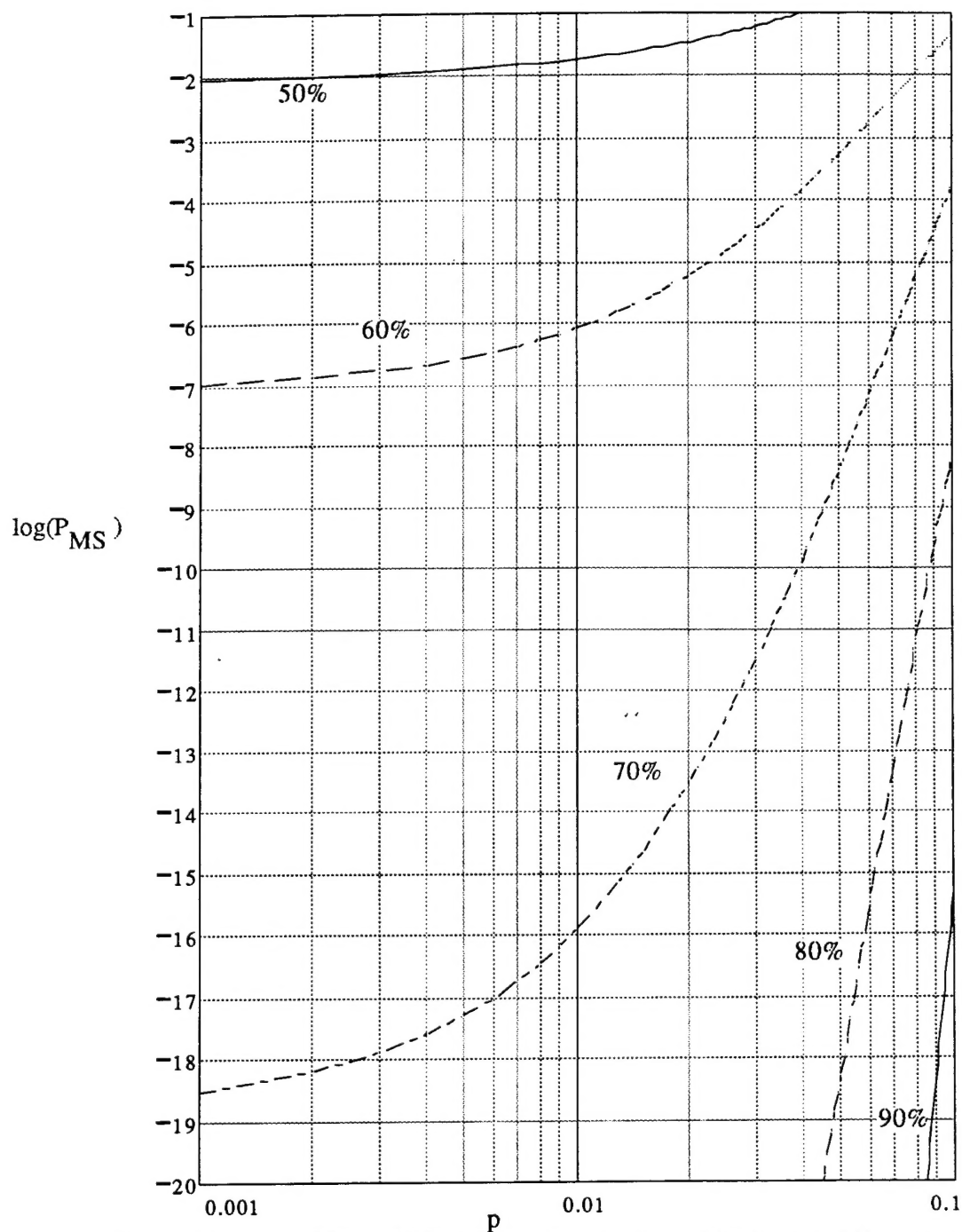
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Figure 13. Probability of Missed Synchronization with Truncated Sequence, versus p, at Threshold T = 100.